

Baryogenesis and Neutron-Antineutron Oscillations

K.S. Babu

Oklahoma State University



2012 Project X Physics Study

Fermilab, June 14-23, 2012

Baryon Number is violated in standard model

- B is a global symmetry of SM classically
- Nonperturbative weak interaction effects lead to B violation **'t Hooft (1976)**

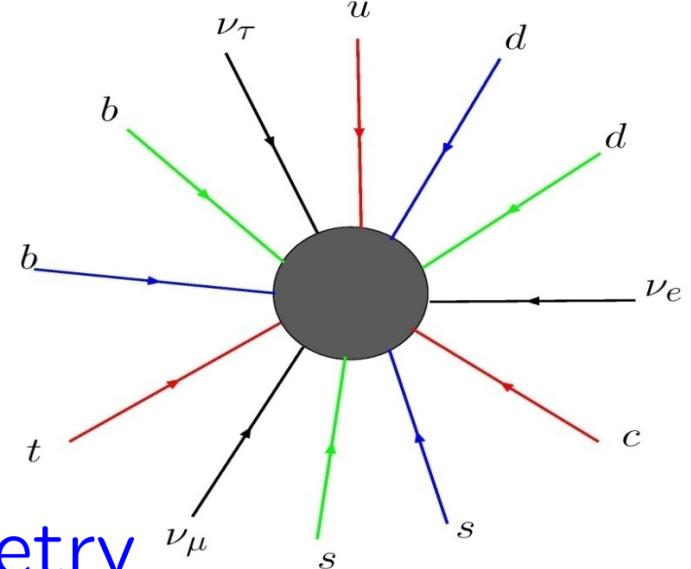
$$\mathcal{O}_{\text{eff}} = c \left(\frac{1}{m_W} \right)^{14} e^{\frac{-2\pi}{\alpha_2}} \prod_{i=1}^3 (\epsilon^{\alpha\beta\gamma} Q_{\alpha L}^i Q_{\beta L}^i Q_{\gamma L}^i L_L^i)$$

- $\Delta B = \Delta L = 3$
Eg: $ppn \rightarrow e^+ e^+ \bar{\nu}$

$$\text{Rate} \propto \left| e^{-\frac{2\pi}{\alpha_2}} \right|^2 \sim 10^{-165}$$

- Relevant for baryon asymmetry

't Hooft (1976)



Kuzmin, Rubakov, Shaposhnikov (1985)

Sphalerons and baryogenesis

- ♦ Sphaleron interaction rate:

$$\Gamma_{\text{sph}} \sim \alpha_W^5 T \sim 10^{-6} T$$

In equilibrium for $T \sim (10^2 - 10^{12}) \text{ GeV}$

Can help generate (or erase) baryon asymmetry

$$\eta = \frac{\eta_B - \eta_{\bar{B}}}{s} \simeq 8 \times 10^{-11} \text{ (BBN, WMAP)}$$

Popular B generation mechanisms

- (Old) GUT scale baryogenesis
 $X \rightarrow ql, \bar{q}\bar{q}$
 X : colored GUT scale Higgs or gauge boson
Asymmetry washed out by sphalerons ($B - L$ conserved)
- Electroweak baryogenesis
Phase transition is too weak (or Higgs mass too low)
Plausible in MSSM, although highly constrained
- Leptogenesis
Heavy ν_R decays: $\nu_R \rightarrow L + H$, $\nu_R \rightarrow \bar{L} + \bar{H}$
Requires $M_R \geq 3 \times 10^9$ GeV (Davidson-Ibarra)
In supersymmetry, gravitino production requires
 $T_{RH} \leq 3 \times 10^7$ GeV
Conflict

Post-sphaleron baryogenesis

Baryogenesis occurs after sphalerons decouple

$$T \leq 200 \text{ GeV}$$

New particle with mass ~ 100 GeV decays violating B

New particle may be boson (S) or fermion (N)

S or N must couple to B violating current

K.S. Babu, R.N. Mohapatra, S. Nasri, Phys. Rev. Lett. 97:131301(2006)

K.S. Babu, R.N. Mohapatra, S. Nasri, Phys. Rev. Lett. 98:161301 (2007)

K.S. Babu, P.S. Bhupal Dev, R.N. Mohapatra, Phys. Rev.D79:015017 (2009)

Possible B violating couplings

$\Delta B = 1$ couplings (e.g. $QQQL$) must decouple before $T \sim 10^{15}$ GeV (proton decay)

$\Delta B = 2$ couplings can be in equilibrium until $T \sim 10^5$ GeV ($n - \bar{n}$) oscillations

$\Delta B = 3$ or higher will be in conflict with nucleosynthesis

Focus on $\Delta B = 2$ processes

S couplings

$$\frac{S}{\Lambda^9} (u_R d_R d_R u_R d_R d_R)$$

$$\frac{S}{\Lambda^9} (Q Q d_R Q Q d_R)$$

$$\frac{S}{\Lambda^9} (Q Q u_R d_R d_R d_R)$$

K.S. Babu, R.N. Mohapatra, W.M. Snow, 2012

S acquires vacuum expectation value
and breaks Baryon number

S_r decays to 6 quarks as well as
into 6 antiquarks

$$S_r \rightarrow 6q, \quad S_r \rightarrow 6\bar{q}$$

Leads to baryon asymmetry

Explicit Model

$$\begin{aligned} L = & \frac{h_{ij}}{2} X d_i^c d_j^c + \frac{f_{ij}}{2} Y u_i^c u_j^c + \frac{g_{ij}}{2} Z (u_i^c d_j^c + u_j^c d_i^c) \\ & + \frac{\lambda_1}{2} S X^2 Y + \frac{\lambda_2}{2} S X Z^2 + h.c \end{aligned}$$

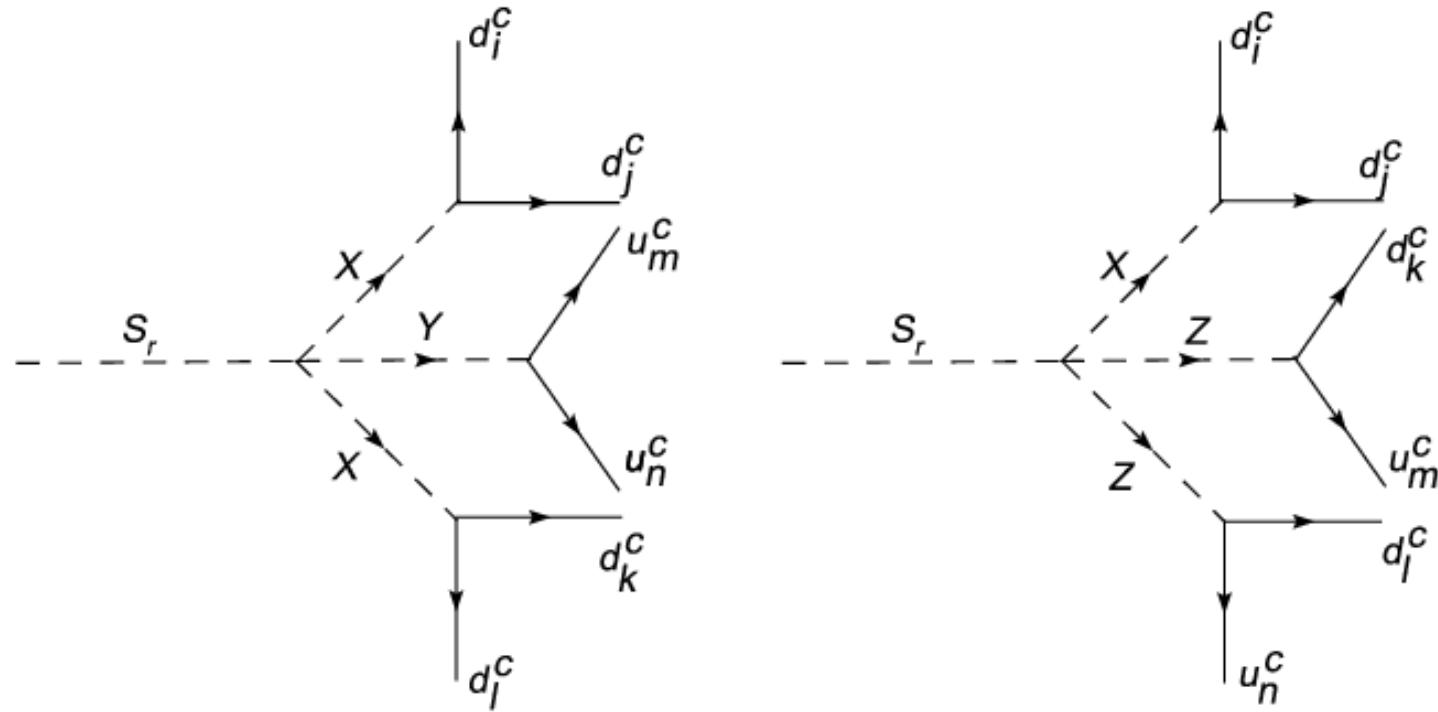
X, Y, Z are color sextet scalars

Part of Higgs sector of Pati-Salam symmetry $SU(4)_c \times SU(2)_L \times SU(2)_R$

Baryon number is broken once $\langle S \rangle \neq 0$

$$S_r \rightarrow 6q, \quad S_r \rightarrow 6\bar{q}$$

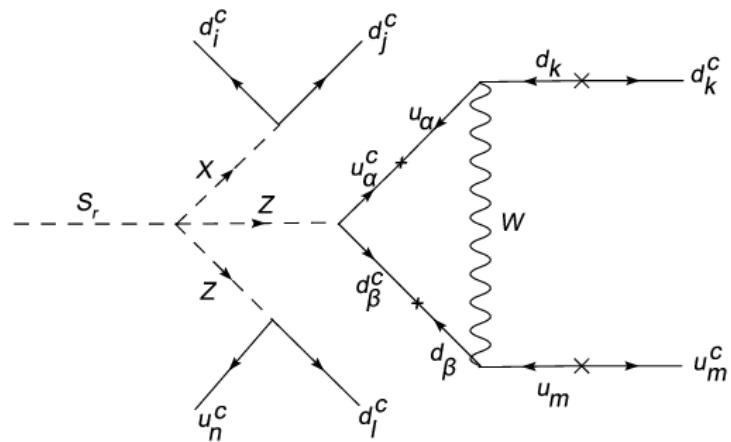
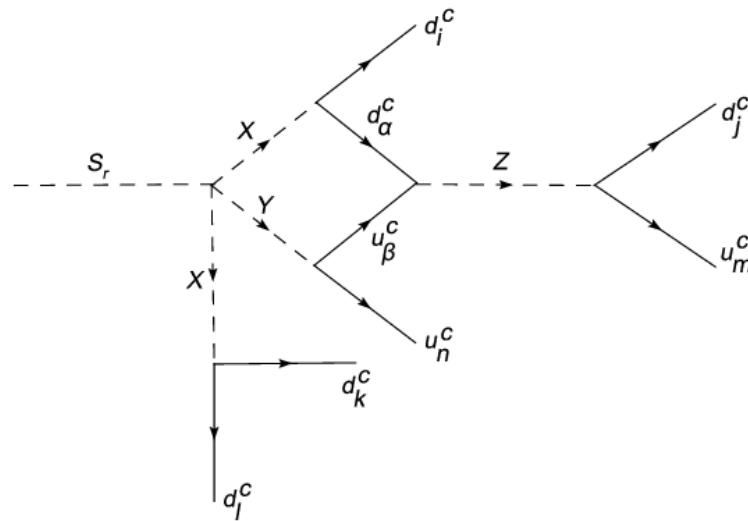
B violating decay of S



$$\Gamma(S_r \rightarrow 6q) \simeq \frac{18P\lambda_2^2 h^2 g^2 M_{S_r}^{13}}{(2\pi)^9 (6M_X)^{12}}$$

$P = 2.05, M_X = 1 \text{ TeV}, M_{S_r} = 100 \text{ GeV}$
 $\rightarrow \tau(S_r) \simeq 10^{-2} \text{ sec}$

CP Asymmetry



Model Predictions

$$\epsilon_B \simeq -\frac{\alpha_2}{4} \frac{\text{ImTr}[g^T \hat{M}_u V g^\dagger V^* \hat{M}_d]}{\text{Tr}(g^\dagger g) m_W^2} \simeq 10^{-8}$$

$$\eta_B \simeq \epsilon_B \frac{T_d}{M_{S_r}}$$

T_d : Temperature when S_r begins to decay

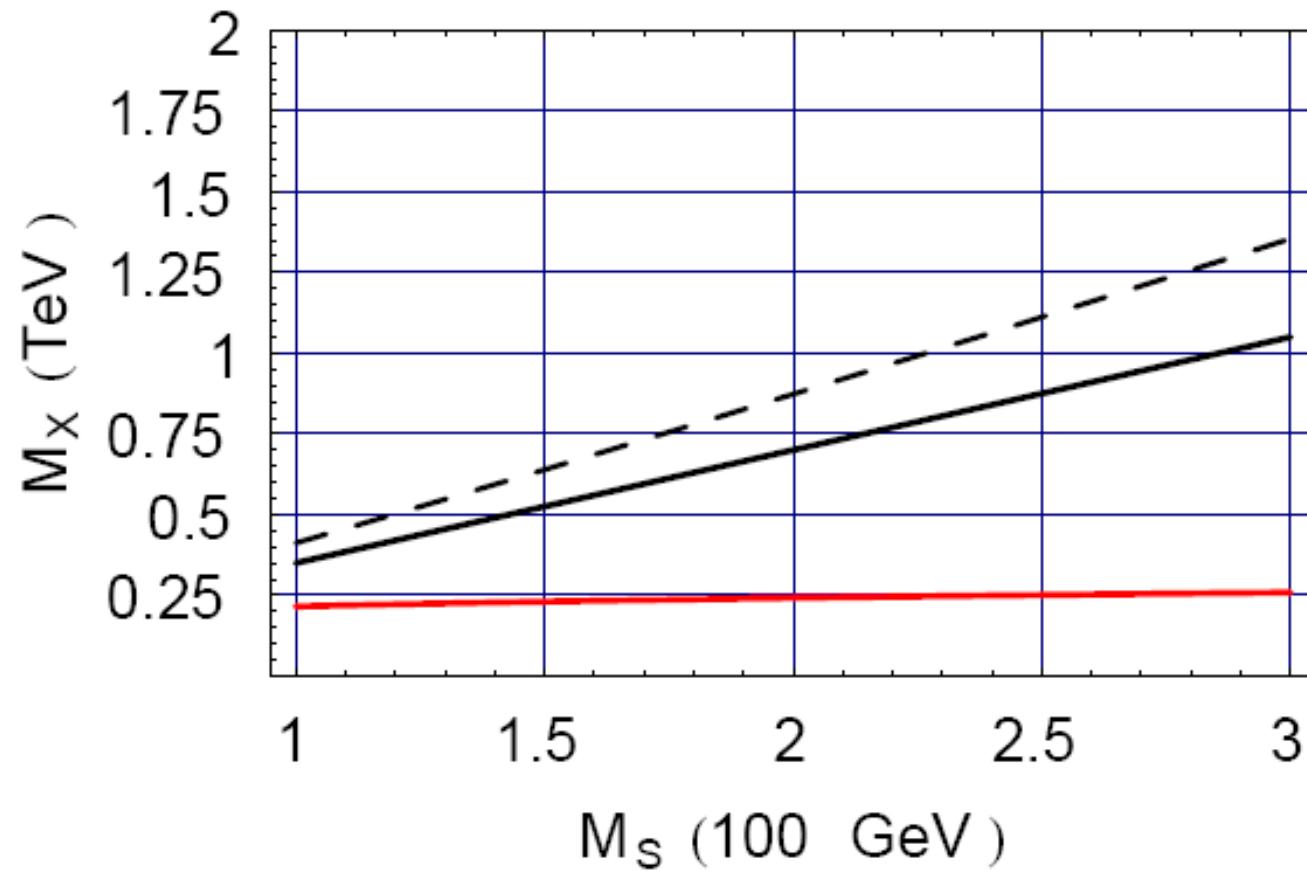
To have $T_d/M_{S_r} \sim 10^{-2}$, and $T_d \geq 200$ MeV,
 $M_{S_r} = 100 - 300$ GeV

Neutron-antineutron transition rate is predicted

Typically $\tau(n - \bar{n}) \sim (10^9 - 10^{11})$ sec

Colored diquarks with mass ~ 1 TeV
accessible to LHC

Sample Parameters



$$\lambda_2 = 0.1, h_{11} = g_{11} = 10^{-5}$$

Red: Current ILL $n - \bar{n}$ limit Black: Correct baryon asymmetry
Black dashed: Nucleosynthesis excludes region above

Revival of GUT scale baryogenesis

In $SU(5)$ decays of heavy gauge bosons of color triplet scalars can generate baryon asymmetry

This asymmetry is however washed out by electroweak sphalerons since $(B - L)$ is preserved

In $SO(10)$, $X \rightarrow Z^*Z^*$ decay occurs, violating $(B - L)$ and can lead to sphaleron-proof baryon asymmetry

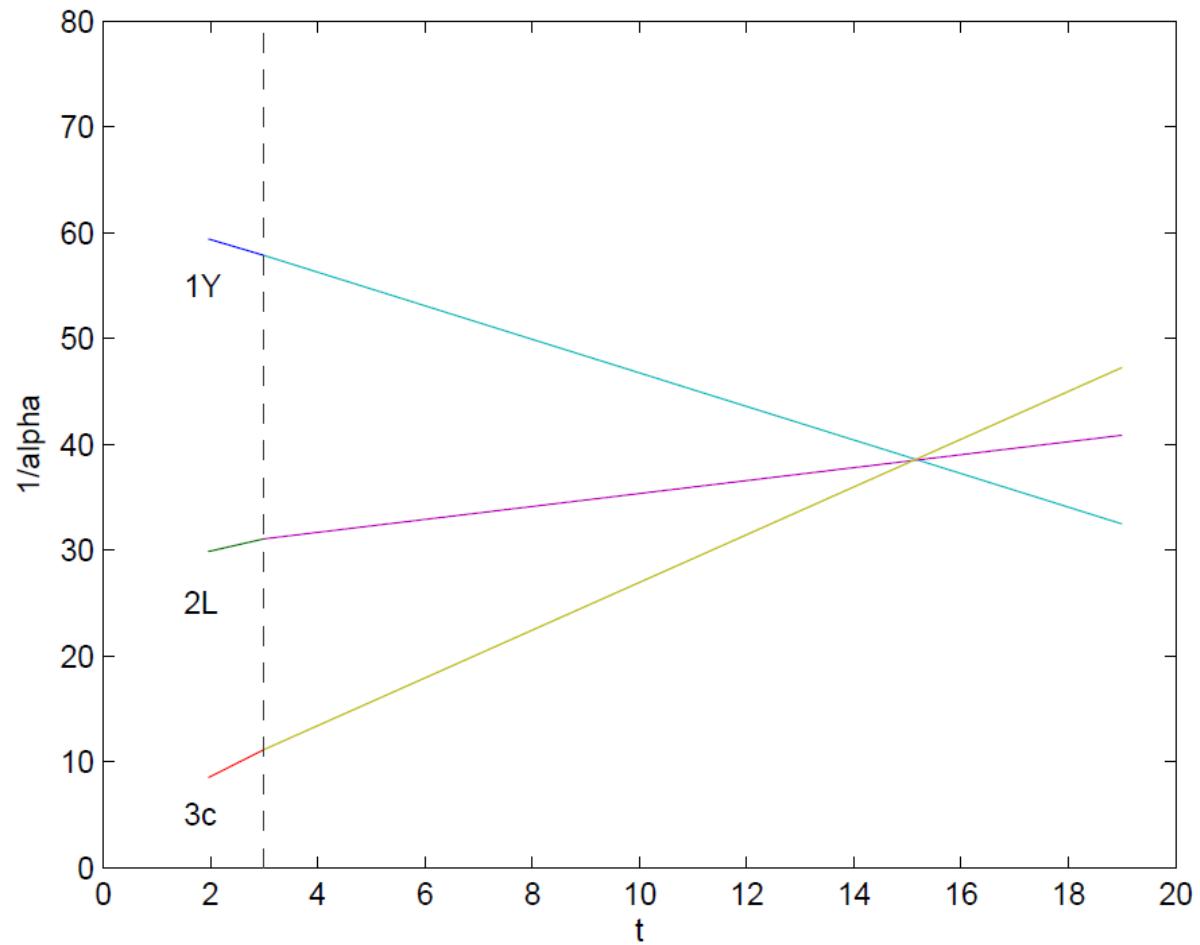
$B - L$ broken by two units: $(B - L)(X) = 2/3$, $(B - L)(Z^*) = -2/3$

If Z has TeV mass, unification occurs without SUSY

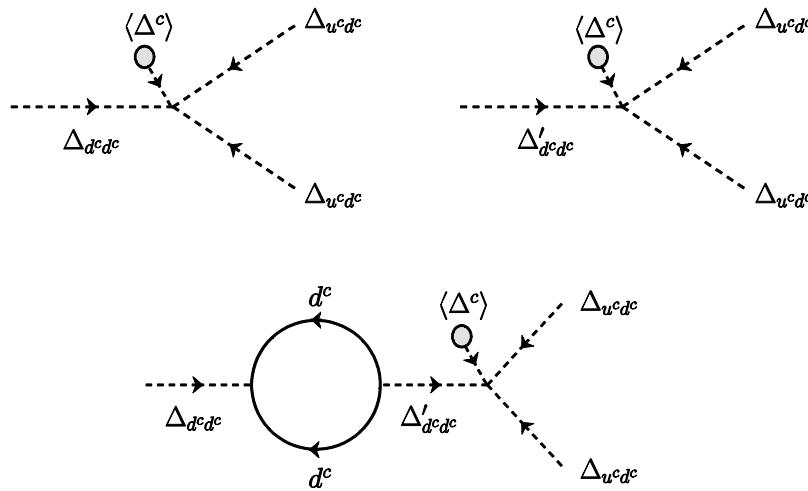
$n - \bar{n}$ oscillation occurs with $\tau_{n-\bar{n}} \sim 10^{10}$ sec.

K.S. Babu, R.N. Mohapatra, arXiv: 1203.5544 [hep-ph]
K.S. Babu, R.N. Mohapatra, 2012

Unification of gauge couplings with $M(Z) = 1\text{TeV}$



GUT Scale (B-L)-genesis



$\Delta_{d^cd^c}$: GUT mass; $\Delta_{u^cd^c}$: TeV mass

Minimal $SO(10)$ models have two $\Delta_{d^cd^c}$ and one $\Delta_{u^cd^c}$
($B - L$) asymmetry of the right order induced

(B-L)-genesis via scalar decay

($B - L$) asymmetry parameter ϵ_{B-L} :

$$\epsilon_{B-L} = (r - \bar{r})(B_1 - B_2)$$

r is branching ratio for $\Delta_{d^c d^c} \rightarrow \Delta_{u^c d^c}^* \Delta_{u^c d^c}^*$

\bar{r} is branching ratio for $\Delta_{d^c d^c}^* \rightarrow \Delta_{u^c d^c} \Delta_{u^c d^c}$

$B_1 = -4/3, \quad B_2 = 4/3$ ($B - L$ of two final states)

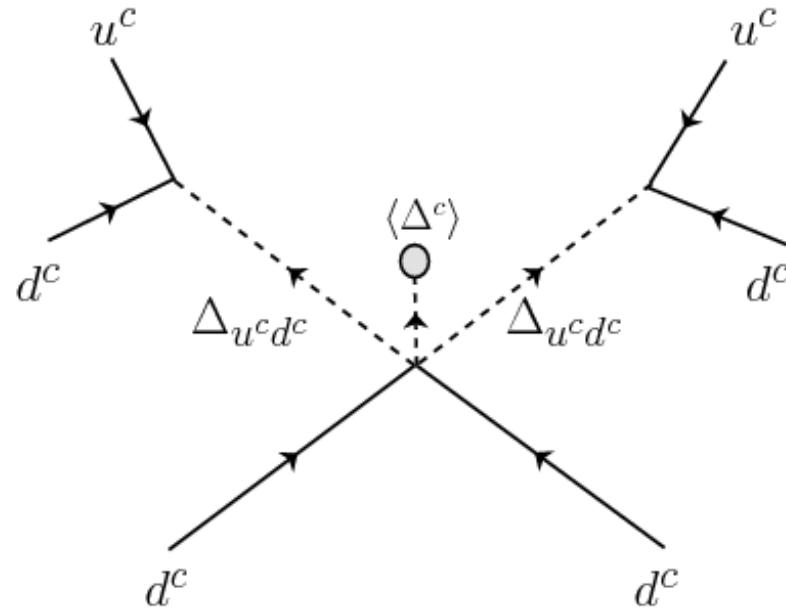
$$\eta = \frac{n_B}{s} \simeq \frac{\epsilon_{B-L}}{g^*} d$$

$$\epsilon_{B-L} \simeq \frac{2}{\pi |\lambda v_R|^2} \text{Tr}(f^\dagger f) \text{Im}[(\lambda v_R)(\lambda' v_R)^*] F \cdot \text{Br}$$

$$F = \frac{M_{d^c d^c}^2}{M_{d^c d^c}^2 - M_{d^c d^c}'^2}$$

$\eta_B \approx 10^{-10}$ naturally generated

N-Nbar oscillations and (B-L)-genesis



$$M_{\delta_{u^c d^c}} = 1 \text{ TeV}, M_{\Delta_{d^c d^c}} = 10^{14} \text{ GeV}, f_{11} = 10^{-3}$$



$$\tau_{n-\bar{n}} = (10^9 - 10^{11}) \text{ sec.}$$

Summary and Conclusions

Post–sphaleron baryogenesis predicts observable $n - \bar{n}$ oscillations

Colored scalars at TeV scale should be accessible to LHC

New GUT scale ($B - L$)–genesis proposed
which is sphaleron–proof

Both models predict

$$\tau(n - \bar{n}) \sim (10^9 - 10^{11}) \text{ sec}$$

$n - \bar{n}$ oscillation experiments can probe a class
of theories which explains the origin of matter
in the universe